

# Topological Spin Dynamics

M. Kläui

Institut für Physik & Materials Science in Mainz  
Johannes Gutenberg-Universität Mainz



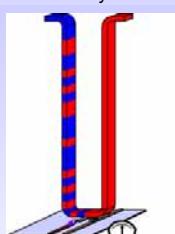
[www.klaeui-lab.de](http://www.klaeui-lab.de)

- Topologically stabilized **Skyrmions**
- Stability and Dynamics of skyrmions
- Efficient topological spin structure manipulation by **Spin Orbit Torques**
- Skyrmion-Racetrack: single skyrmion manipulation by Spin Orbit torques
- Dynamic imaging of skyrmion motion → the **Skyrmion Hall Effect**
- Spin Orbit Torques in **Antiferromagnets**



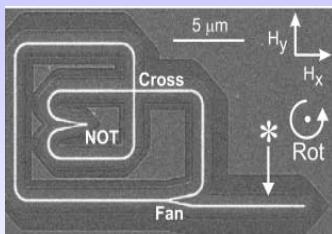
## Topological spin structures – exciting physics & non-volatile low power devices

Racetrack  
DW or Skyrmion



Domain Wall Racetrack:  
Parkin et al., Science **320**, 190 ('08)  
Skyrmion Racetrack:  
Fert et al., Nature Nano **8**, 152 ('13)

Spin structure Logic



D. A. Allwood et al., Science **309**, 1688 ('05)

Domain Wall Sensors



R. Mattheis et al., IEEE Trans. Magn. **45**, 3792 (2009)

A. Bisig, MK et al., Nature Comm. **4**, 2328 (2013)

## Challenges for Spintronics Devices:

**Stability** – Long term information retention

**Manipulation** – Efficiency and speed

**No stray fields** – Antiferromagnetic Spintronics

Mathias Kläui Skyrmionics, 9.8.2017

## 2. Chiral exchange coupling – Dzyaloshinskii-Moriya interaction

**Chiral exchange coupling** leads to special **stable spin structures**

The diagram shows a 3D structure of a magnetic stack. At the top is a 'Ferromagnet (FM)' layer with white spheres representing spins. Below it is a 'Heavy Metal Layer (HL) with large spin-orbit interaction (SOI)' represented by blue spheres. A red dashed arrow labeled  $D_{12}$  indicates the coupling between two spins  $M_1$  and  $M_2$  in the FM layer, which is mediated by an 'Atom with large SOI' located in the HL layer. A small inset shows a circular pattern of spins with arrows pointing in various directions.

- Two spins in the ferromagnet are coupled via an atom with large SOI in a heavy metal layer → Dzyaloshinskii-Moriya interaction (DMI)
- Favours chiral spin canting → Chiral Domain Walls & Skyrmions!

I. Dzyaloshinsky, J. Phys. Chem. Solids **4**, 241 (1958); T. Moriya, Phys. Rev. Lett. **4**, 228 (1960)

Mathias Kläui Skyrmionics, 9.8.2017

## 2. Chiral exchange coupling – Dzyaloshinskii-Moriya interaction

**Domain Imaging:**

0.50 mJ/m<sup>2</sup> 1.00 mJ/m<sup>2</sup> 1.25 mJ/m<sup>2</sup>  
1.50 mJ/m<sup>2</sup> 1.75 mJ/m<sup>2</sup>

**Asymmetric Switching:**

$M/M_z$  (arb. unit) vs  $B_x$  (mT)

$\Delta B_c/B_c$  (%) vs  $B_x$  (mT)

$\alpha = 15^\circ$

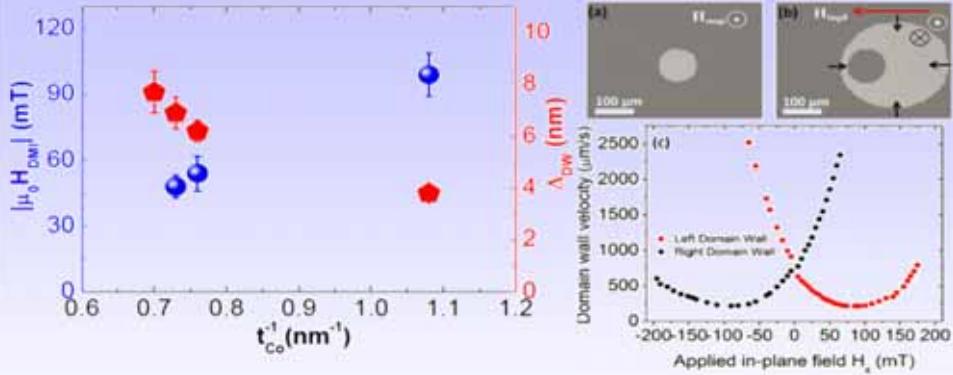
$\alpha = 30^\circ$

<sup>1</sup>S. Woo, MK et al., Nat. Mater. **15**, 501 (2016); <sup>2</sup>D. Han, MK et al., Nano Lett. **16**, 4438 (2016)  
I. Lemesh et al., Phys. Rev. B **95**, 174423 (2017)

- DMI sets minimum domain width → spin spiral ground state<sup>1</sup>  
→ measurement of DMI from magnetic imaging<sup>1,2</sup>
- DMI breaks symmetry for switching by in-plane field → DMI measurement<sup>3</sup>
- Other methods include BLS, bubble expansion<sup>4</sup>, DW motion and others

<sup>2</sup>M. Bacani arxiv:1609.01615 <sup>4</sup>S. Je et al., PRB **88**, 214401 ('13); S. Jaiswal, MK et al., APL **111**, 22409 ('17)

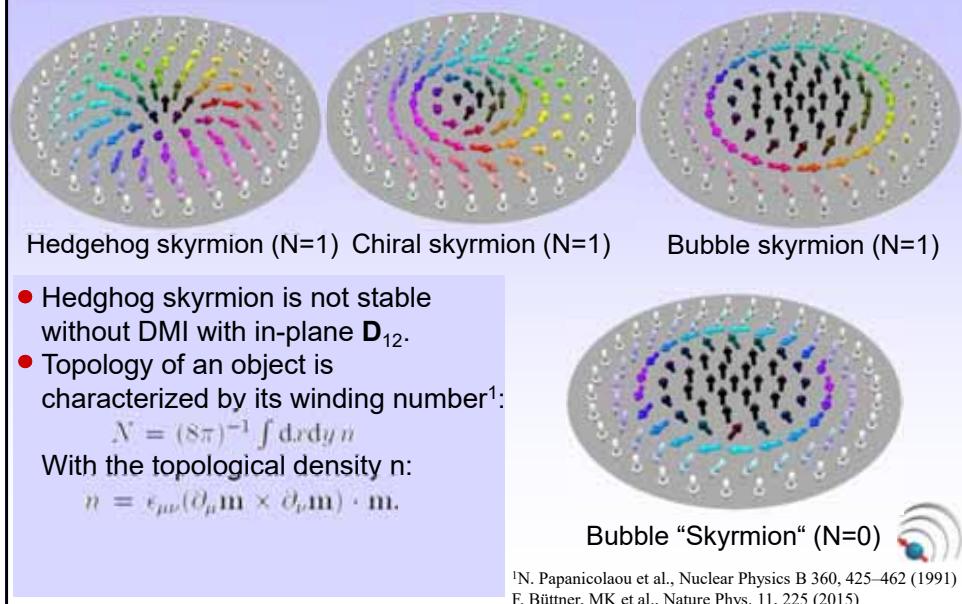
## 2. Chiral exchange coupling – Dzyaloshinskii-Moriya interaction



- DMI sensitive to interfaces: scaling with 1/thickness → interface effect<sup>1</sup>
- Comparison of different measurement schemes<sup>1</sup>:
  - Domain Widths vs. Bubble Expansion:  APL **111**, 22409 (2017)
  - Domain Wall Motion vs. Spin Waves  AIP Adv. **7**, 065317 (2017)
- DMI is tuned by 2p-5d hybridization<sup>2</sup> and  $\text{Co}_{20-40}/\text{Fe}_{40-60}\text{B}_{20}$  composition<sup>1</sup>

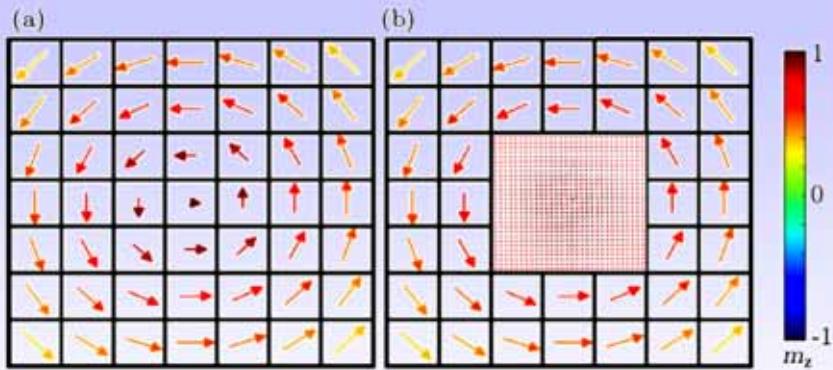
<sup>1</sup>S. Jaiswal et al., APL **111**, 22409 ('17); R. LoConte et al., AIP Adv. **7**, 065317 ('17); <sup>2</sup>R. LoConte et al., PRB **91**, 014433 ('15)

## 2. Spin Structures stabilized by the chiral DMI



<sup>1</sup>N. Papanicolaou et al., Nuclear Physics B **360**, 425–462 (1991)  
F. Büttner, MK et al., Nature Phys. **11**, 225 (2015)

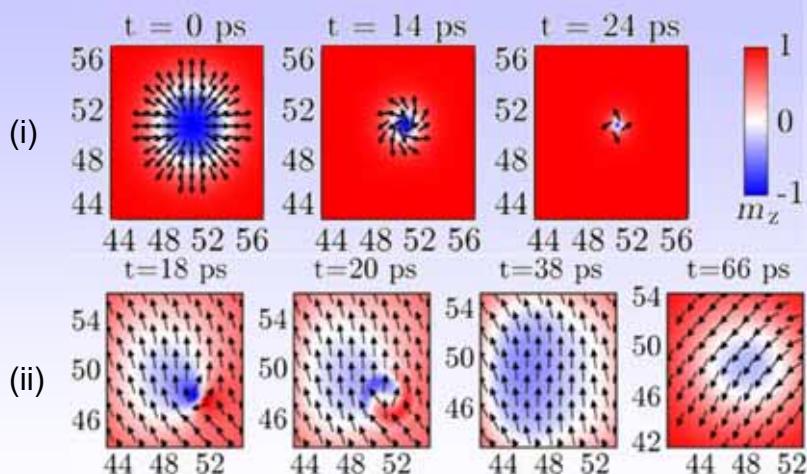
## 2. Skyrmion stability



- To calculate spin structures with large magnetization gradients more realistically, use a multiscale approach (micromagnetics + Heisenberg).<sup>1</sup>
- This also allows for calculating thermal properties due to realistic spin wave spectrum.

<sup>1</sup>A. De Lucia, MK et al., PRB **94**, 184415 (2016); <sup>2</sup>A. de Lucia, MK et al., PRB **96**, 020405(R) (2017)

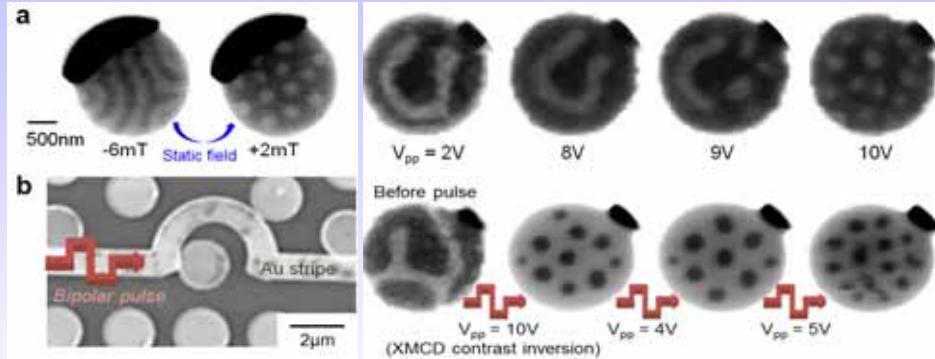
## 2. Skyrmion stability



- 2 Annihilation mechanisms<sup>2</sup>: (i) shrinking to zero & (ii) nucleation of a Bloch line.
- Note that even in a continuum model, there is only a finite energy barrier to annihilating a skyrmion via a zero diameter (F. Büttner et al., arxiv:1704.08489).

<sup>1</sup>A. De Lucia, MK et al., PRB **94**, 184415 (2016); <sup>2</sup>A. de Lucia, MK et al., PRB **96**, 020405(R) (2017)

## 2. Generating Skyrmion Lattices in multilayer stacks

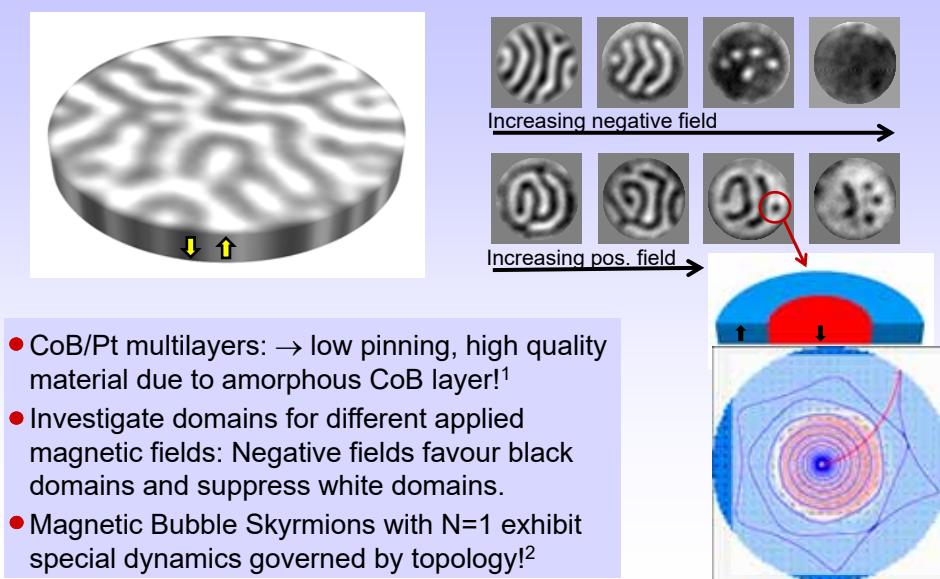


<sup>1</sup>S. Woo, MK et al., Nature Mater. **15**, 501 (2016) (with G. Beach & P. Fischer);

- Switch from the stripe phase to the skyrmion lattice by demagnetization: first observation of a skyrmion lattice at room temperature<sup>1</sup>
- Continuous film: skyrmion lattice periodicity is determined by A/D
- Confined disc geometry: skyrmion lattice periodicity commensurate with disc radius.
- Size depends on magnetic field and materials system (see also Refs. <sup>1-3</sup>)

<sup>1</sup>W. Jiang et al., Science **349**, 283 (2015); <sup>2</sup>C. Moreau et al., Nat. Nano. **11**, 444; <sup>3</sup>O. Boulle et al., ibid **11**, 449

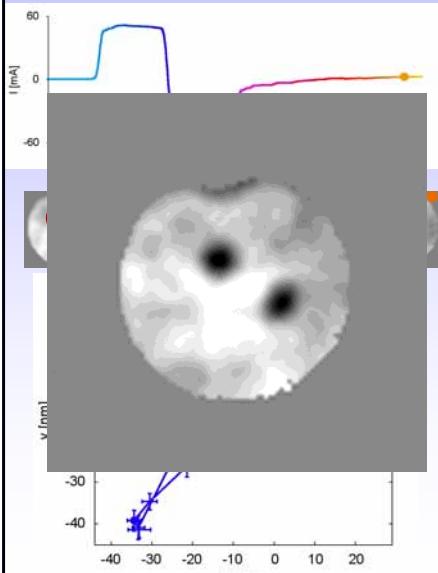
## 2. Magnetic Skyrmion Dynamics in confined high anisotropy discs



- CoB/Pt multilayers: → low pinning, high quality material due to amorphous CoB layer!<sup>1</sup>
- Investigate domains for different applied magnetic fields: Negative fields favour black domains and suppress white domains.
- Magnetic Bubble Skyrmions with N=1 exhibit special dynamics governed by topology!<sup>2</sup>

<sup>1</sup>F. Büttner, MK et al., Nature Phys. **11**, 225 ('15); <sup>2</sup>C. Moutafis et al., PRB **79**, 224429 ('09).

## 2. Magnetic Skyrmion Dynamics in confined high anisotropy discs



- Initial magnetization can be set by a global static field.
- Constant external field applied to generate 2 skyrmion state.
- Bipolar field pulse ( $\pm 25$  mT pulse, 3ns)
- Tracking skyrmion center position to plot bubble trajectory.
- Skyrmion comes close to zero position
- Relaxation on a spiralling trajectory  
⇒ gyrotropic motion, predicted in [1,2].
- Trajectory allows us to identify the spin structure as a N=1 skyrmion.

<sup>1</sup>L Makhfudz et al., PRL **109**, 217201 (2012); <sup>2</sup>F. Büttner, MK et al., Nature Phys. **11**, 225 (2015)

### Topological spin structures – exciting physics & non-volatile low power devices

**Racetrack**  
DW or Skyrmion

Domain Wall Racetrack:  
Parkin et al., Science **320**, 190 ('08)  
Skyrmion Racetrack:  
Fert et al., Nature Nano **8**, 152 ('13)

**Spin structure Logic**

D. A. Allwood et al., Science **309**, 1688 ('05)

**Domain Wall Sensors**

R. Mattheis et al., IEEE Trans. Magn. **45**, 3792 (2009)  
A. Bisig, MK et al., Nature Comm. **4**, 2328 (2013)

**Challenges for Spintronics Devices:**

Stability – Long term information retention

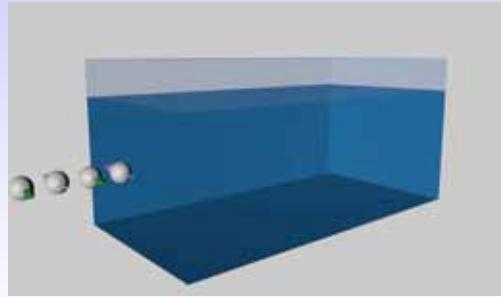
Manipulation – Efficiency and speed

No stray fields – Antiferromagnetic Spintronics

### 3. Interface spin – orbit torques - Theory

Spin-orbit Torque Origin 1 - Spin Hall Effect (SHE):

J. Sinova et al., Rev. Mod. Phys. **87**, 1213 (2015)



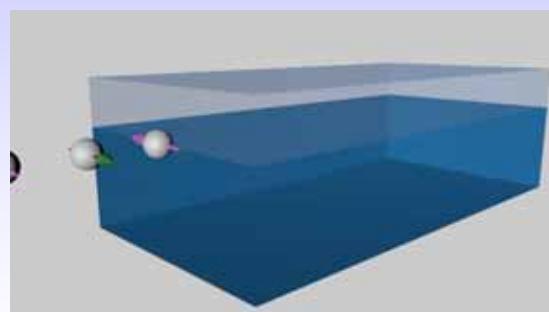
- In a heavy metal (HL=Ta, W, etc.): charge current generates spin current  
→ spin accumulation diffuses into the ferromagnet → measured by THz<sup>1</sup>
- These spins exert new damping-like and field-like **spin orbit torques<sup>2</sup>**

<sup>1</sup>T. Seifert, MK et al., Nat. Phot. **10**, 483 (2016); <sup>2</sup>A. Brataas et al., Nat. Nano **9**, 86 ('14); Liu et al., PRL **109**, 96602 ('12);

### 3. Interface spin – orbit torques - Theory

Spin-orbit Torque Origins:

- Origin 1:  
Spin Hall Effect (bulk property)



- Origin 2:  
Inverse Spin Galvanic Effect (interface property)

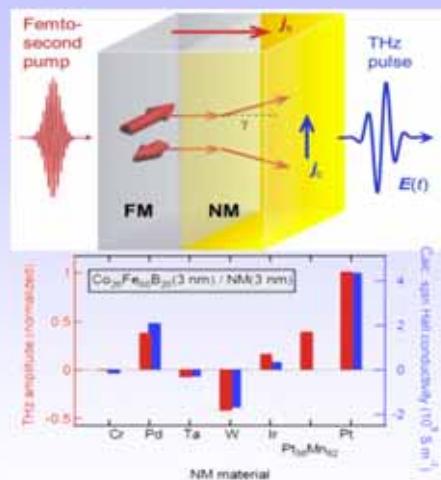
- Additionally the Inverse Spin Galvanic Effect generates a non-equilibrium spin density for electrons flowing at the interface.<sup>1</sup>
- → interaction by exchange manipulates magnetization → SOT!

<sup>1</sup>K. Shen et al., Phys. Rev. Lett. **112**, 096601 (2014); V. M. Edelstein, Sol. State Comm. **73**, 233 (1990)

### 3. Spin – orbit torques – THz quantification

#### Spin-orbit Torque Origins:

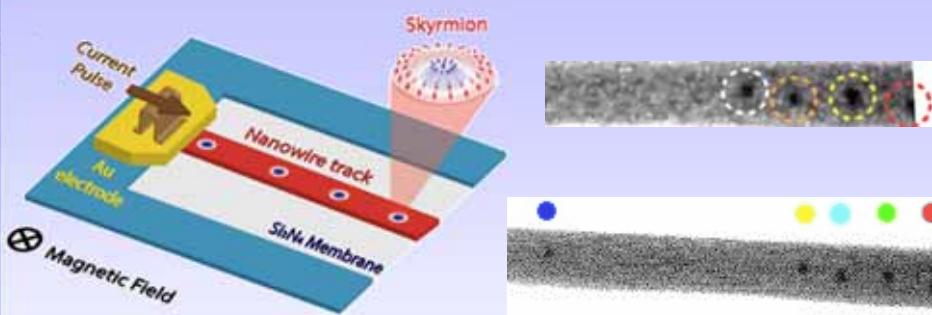
- Origin 1:  
Spin Hall Effect (bulk property)



- Novel Method to measure spin-orbit torques: THz spectroscopy<sup>1</sup>  
→ Good agreement between measurements and theoretical calculations!
- Maximize SOTs in Pt/CFB/Ta&Pt/CFB/W with opposite SHA of Pt & W/Ta<sup>2</sup>

<sup>1</sup>T. Seifert, MK et al., Nat. Photon. **10**, 483 (2016); <sup>2</sup>T. Seifert, MK et al., Appl. Phys. Lett. **110**, 252402 (2017)

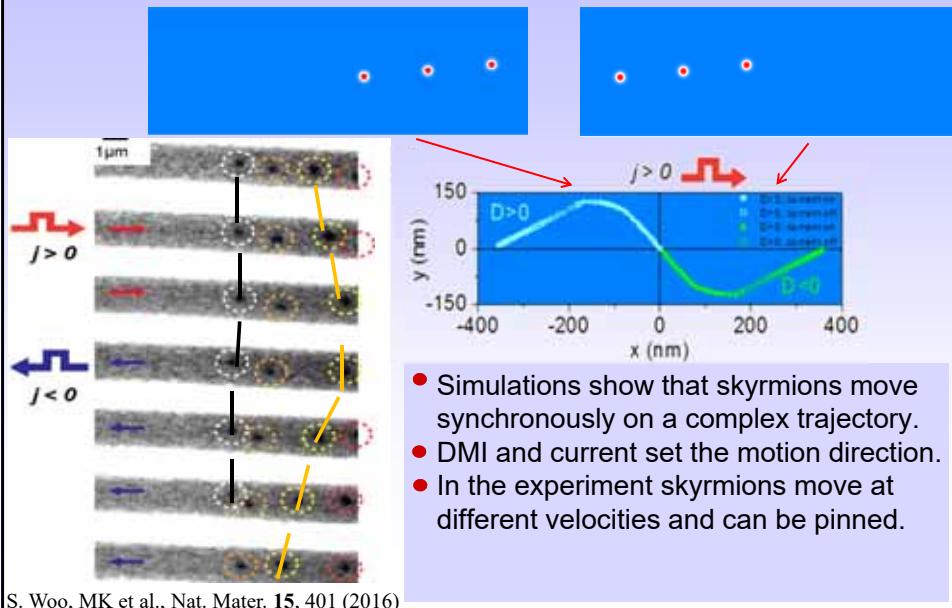
### 4. Skyrmion Racetrack



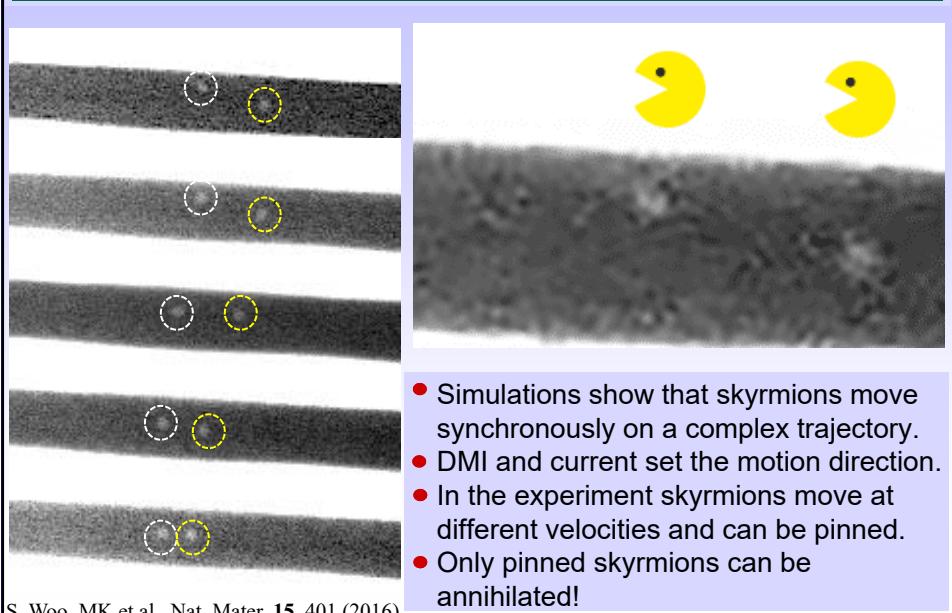
- Skyrmion racetrack<sup>1</sup>: advantages compared to a DW-based racetrack:  
total magnetization does not change with skyrmion motion  
→ less susceptible to stray fields.
- Topological protection of skyrmions → more reliable motion?
- Nanowire is patterned out of Pt/Co/Ta ( $\mu\text{m}$  width)<sup>2</sup>
- Single skyrmions can be moved by spin orbit torques on the nano-track

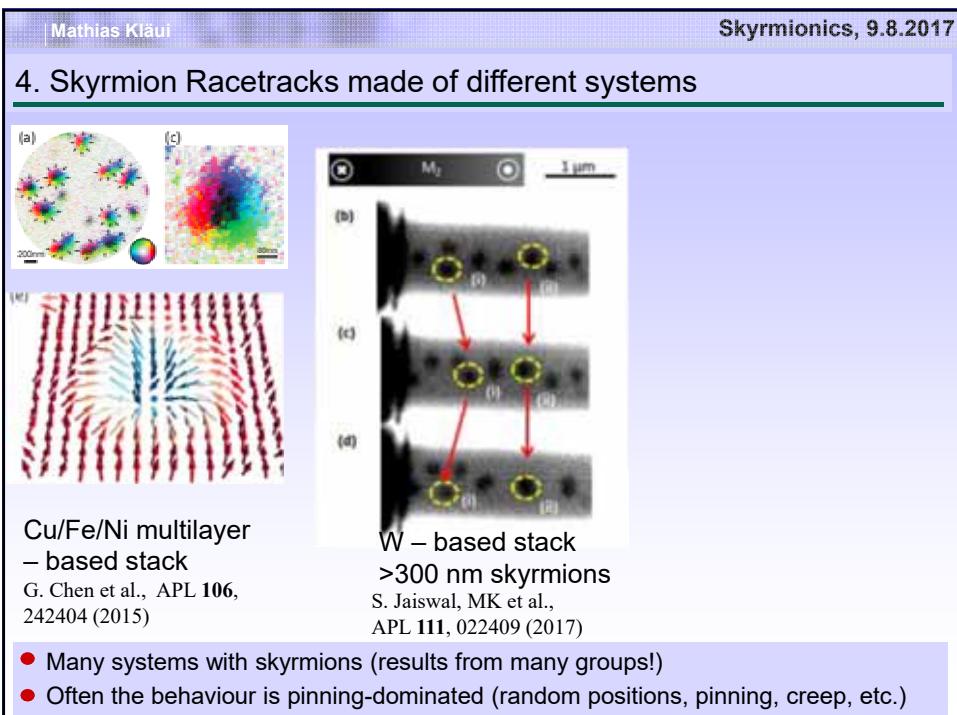
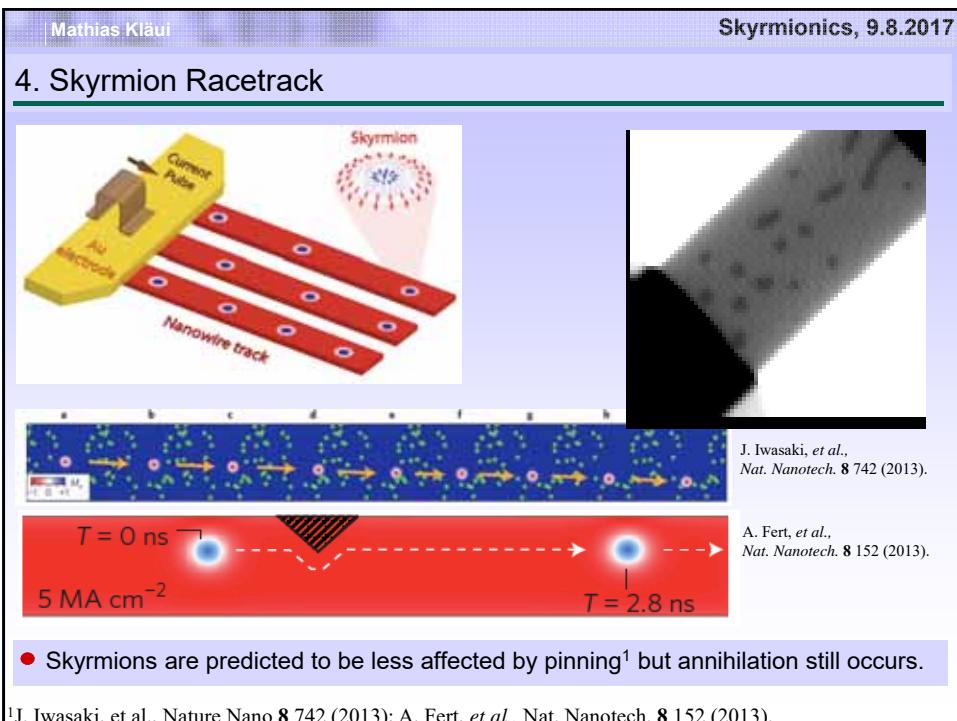
<sup>1</sup>A. Fert et al., Nature Nano **8**, 152 (2013); <sup>2</sup>S. Woo, MK et al., Nature Mater. **15**, 401 (2016)

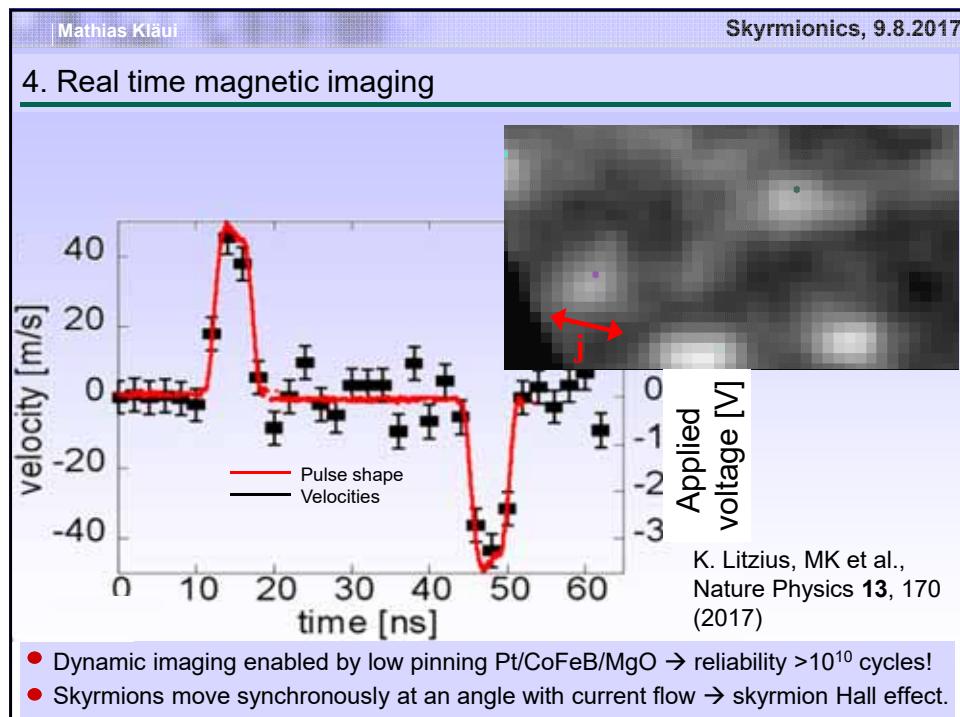
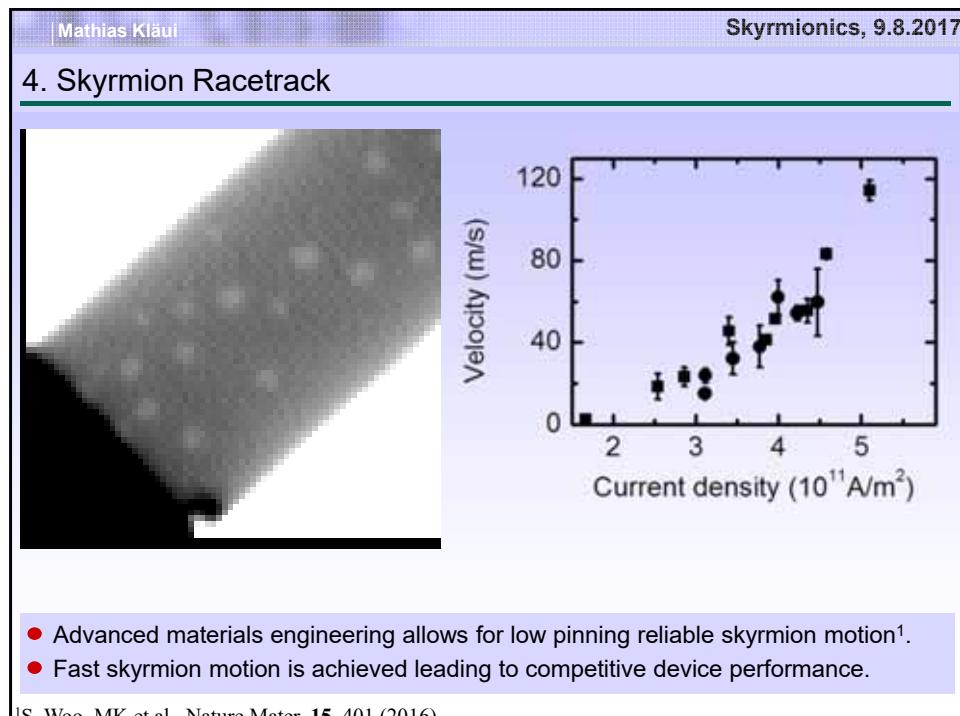
#### 4. Skyrmiон Racetrack

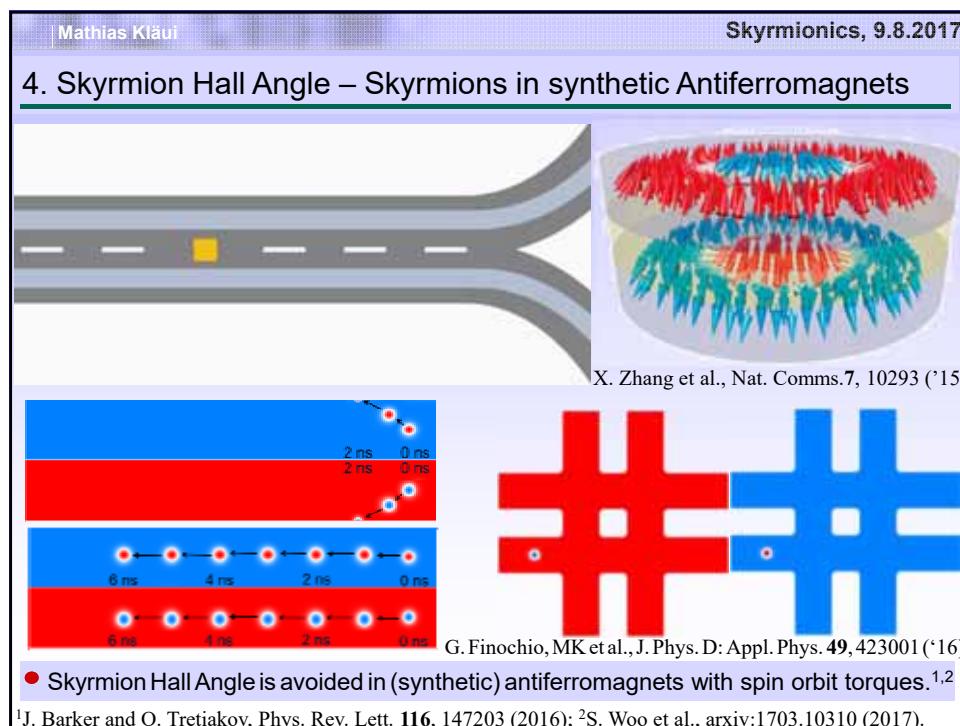
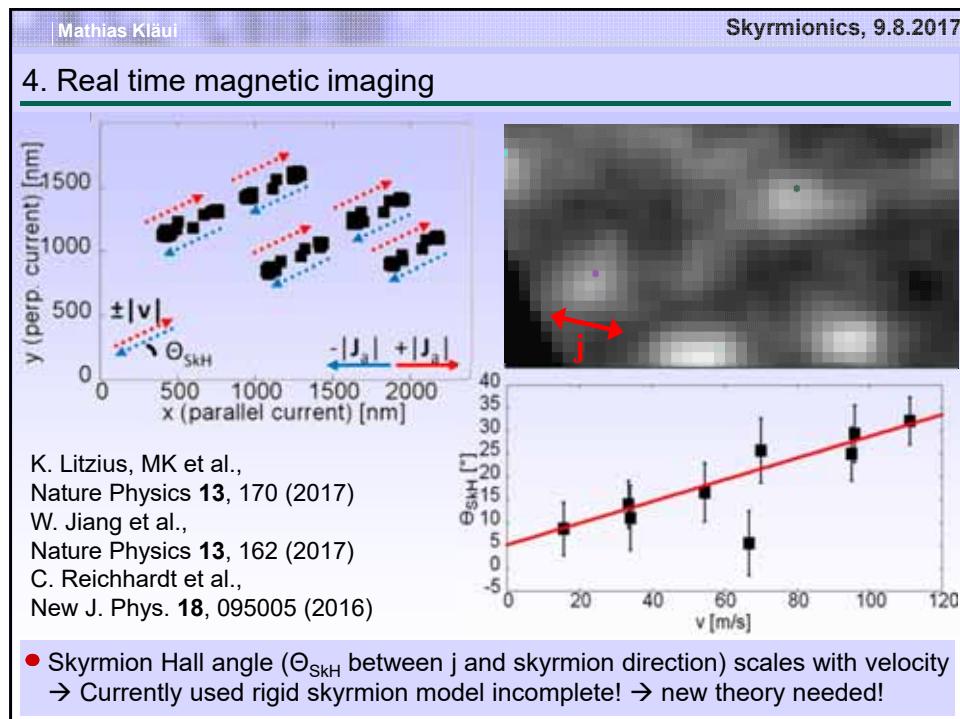


#### 4. Skyrmiон Racetrack - Stability



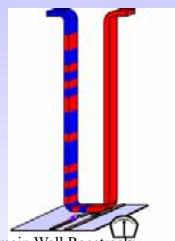






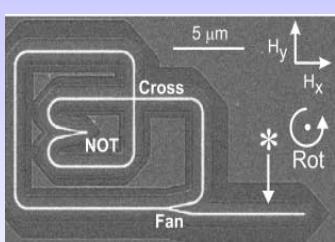
## Topological spin structures – exciting physics & non-volatile low power devices

Racetrack  
DW or Skyrmion



Domain Wall Racetrack:  
Parkin et al., Science 320, 190 ('08)  
Skyrmion Racetrack:  
Fert et al., Nature Nano 8, 152 ('13)

Spin structure Logic



D. A. Allwood et al., Science 309, 1688 ('05)

Domain Wall Sensors



R. Mattheis et al., IEEE Trans. Magn. 45, 3792 (2009)  
A. Bisig, MK et al., Nature Comm. 4, 2328 (2013)

### Challenges for Spintronics Devices:

**Stability** – Long term information retention

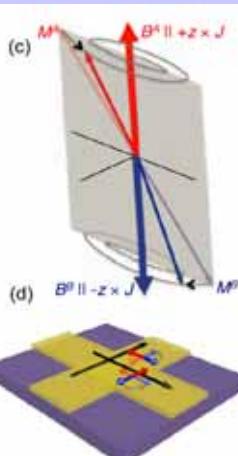
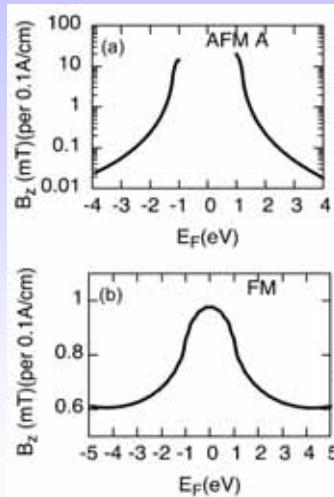
**Manipulation** – Efficiency and speed

**No stray fields – Antiferromagnetic Spintronics**

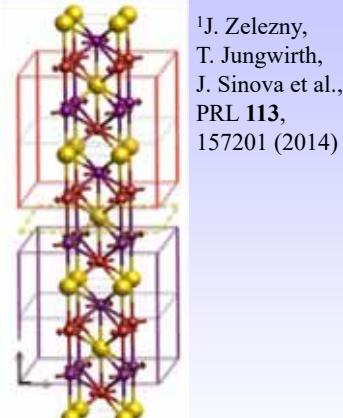
Mathias Kläui

Skyrmionics, 9.8.2017

### 5. Development of antiferromagnetic materials for spin – orbit effects



<sup>1</sup>J. Zelezny,  
T. Jungwirth,  
J. Sinova et al.,  
PRL 113,  
157201 (2014)

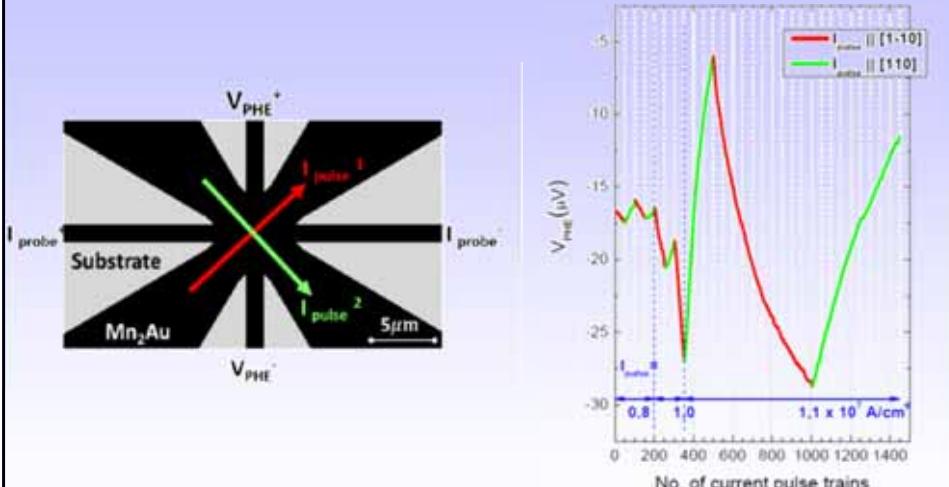


A. Sapozhnik, S. Bodnar  
with H. Elmers, H. Zabel, M. Jourdan

- Prediction of bulk spin orbit torques acting on the Néel order in AFM Mn<sub>2</sub>Au<sup>1</sup> → manipulation of magnetization using electric currents (first observed in CuMnAs<sup>2</sup>).

<sup>1</sup>P. Wadley, T. Jungwirth et al., Science 351, 587 (2016)

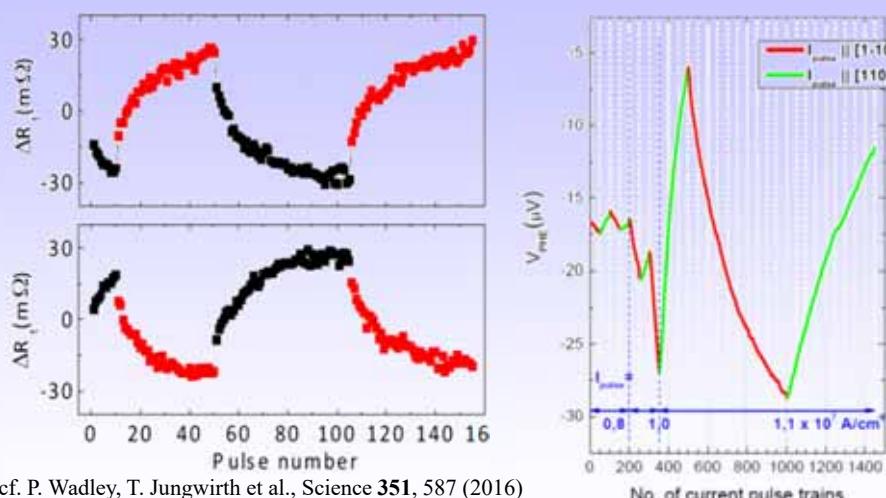
## 5. Bulk spin orbit torque switching in $\text{Mn}_2\text{Au}$



- Bulk Néel spin orbit torques have been predicted to switch the Néel vector.
- Non-linear switching as a function of current density → heating effects important?

S. Bodnar, MK et al., arxiv:1706.02482; M. Jourdan, MK et al., J. Phys. D: Appl. Phys. **48**, 385001 (2015)

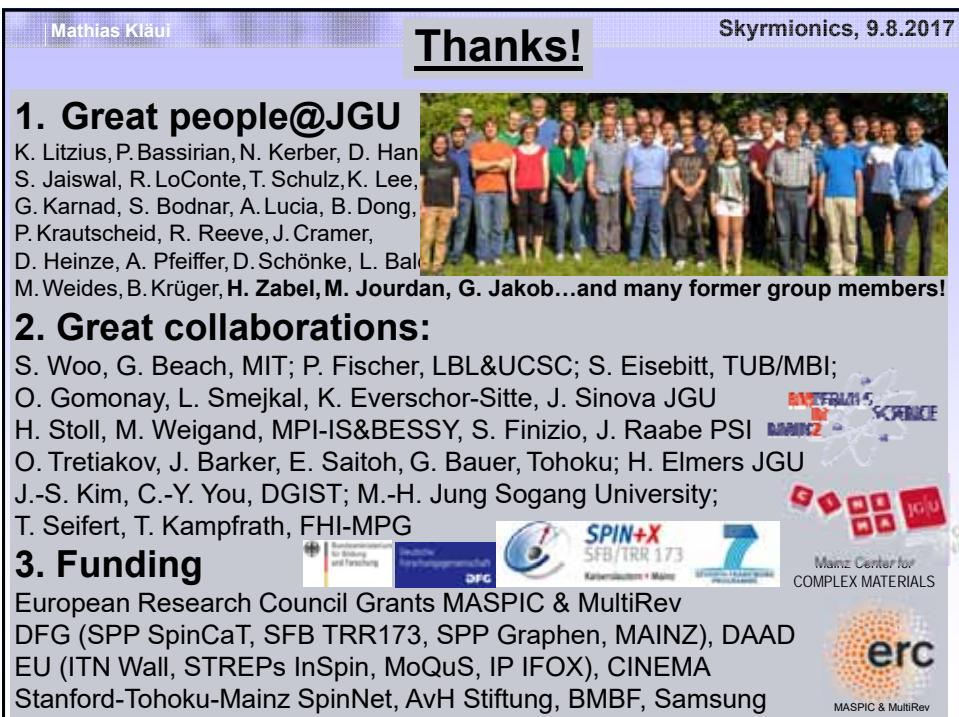
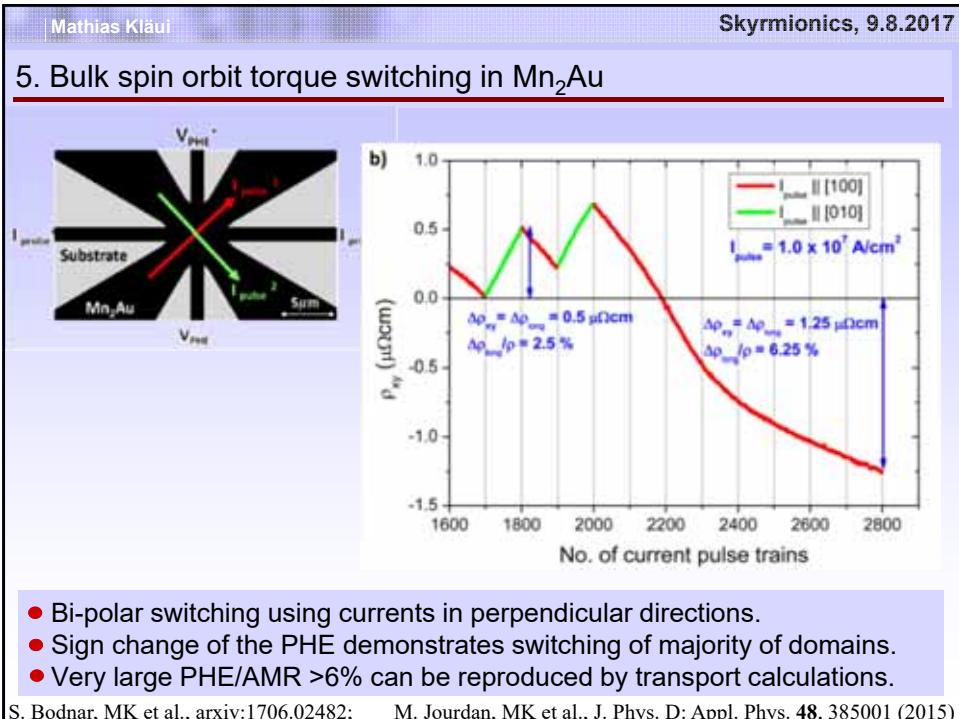
## 5. Bulk spin orbit torque switching in $\text{Mn}_2\text{Au}$



cf. P. Wadley, T. Jungwirth et al., Science **351**, 587 (2016)

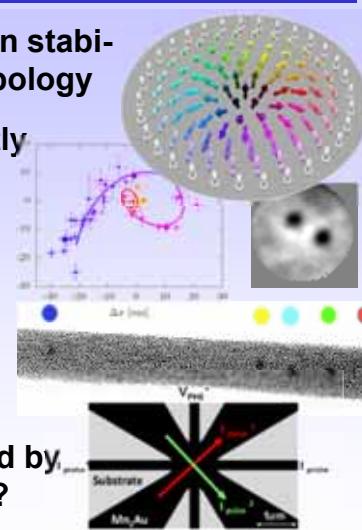
- Bulk Néel spin orbit torques have been predicted to switch the Néel vector
- Non-linear switching as a function of current density → heating effects important?

S. Bodnar, MK et al., arxiv:1706.02482; M. Jourdan, MK et al., J. Phys. D: Appl. Phys. **48**, 385001 (2015)



## Summary:

- The Dzyaloshinskii-Moriya interaction stabilizes spin structures with defined topology
- Skyrmions dynamics depends directly on the topological winding number
- Spin-orbit torques lead to ultra-efficient spin manipulation
- Skyrmion racetrack is realized with motion of single skyrmions by SOTs
- Antiferromagnets can be manipulated by Néel spin orbit torques & skyrmions?



**Papers:** Nature Phys. **11**, 225 (2015); Nature Mater. **15**, 501 (2016); Nature Phys. **13**, 170 (2017)

**Reviews:** Domain Walls: J. Phys. Cond. Mat. **20**, 313001 (2008);

Spin Torque: Mater. Sci. Eng. R **72**, 159 (2011); Skyrmions: J. Phys. D: Appl. Phys. **49**, 423001 (2016)

[www.klaeui-lab.de](http://www.klaeui-lab.de)

